IEEE Aerospace Conference 2019

Regolith Particle Erosion of Material in Aerospace Environments

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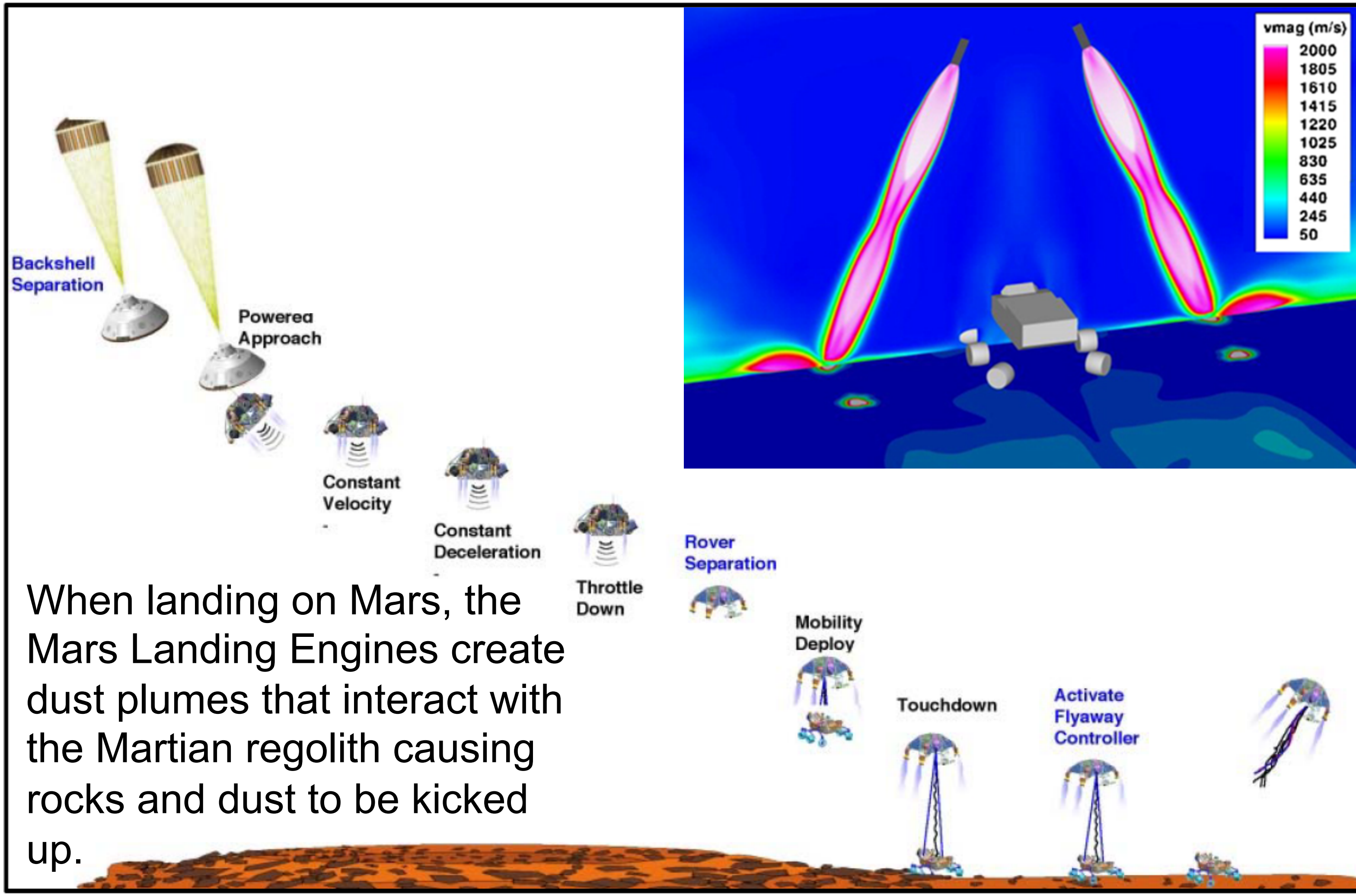
Jet Propulsion Laboratory
California Institute of Technology

Outline

- Background
  - Extreme landing environment, which put the rover and the material at risk
- Material Selection
- Test Facility
  - Test matrix was created based on capabilities and requirements
- Results
  - Paint
  - Flex Cable
  - Composite
  - Fiber Optic Cable
- Conclusion

Background

Entry Descent and Landing (EDL)



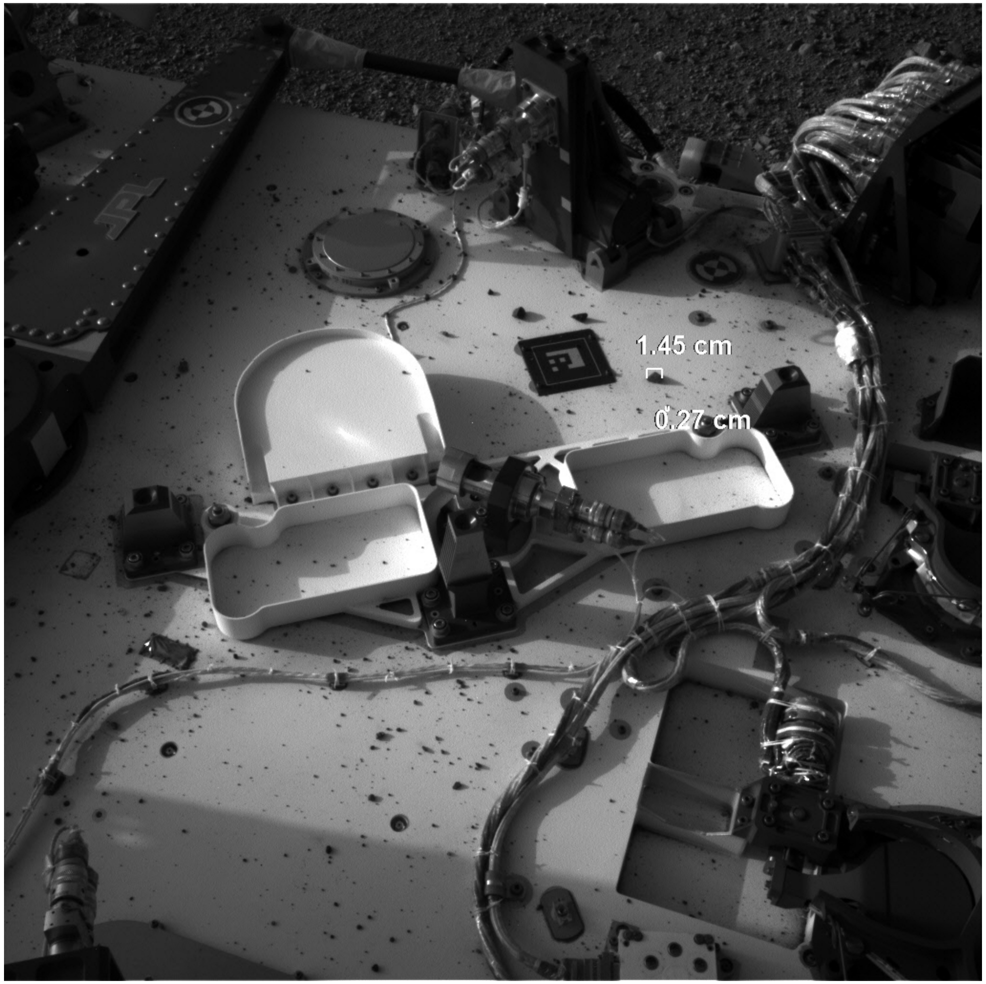
When landing on Mars, the Mars Landing Engines create dust plumes that interact with the Martian regolith causing rocks and dust to be kicked up.

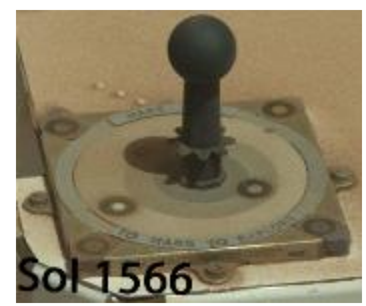
Images courtesy of:

Sengupta, Anita, J. Kulleck, J. Van Norman, and M. Mehta. "Thermal Coating Erosion in a Simulated Martian Landing Environment." *Wear*, vol. 270, no. 5-6, 2011, pp. 335–343., doi:10.1016/j.wear.2010.09.013.

M. Schoenenberger, A. Dyakonov, P. Buning, W. Scallion, and J. Van Norman. Aerodynamic challenges for the Mars Science Laboratory entry descent and landing, in: 41st AIAA Thermophysics Conference, 22–25 June, San Antonio, Texas, 2009.

Particle Migration on the Rover Deck





Mars Science Laboratory (MSL) immediately after landing (left) and throughout the mission life (right).

Images courtesy NASA/JPL

Materials Tested

- Materials that were considered at risk
  - Exposure/location
  - Durability
  - Single point failure
- Tested to determine survivability

- Thermal Control Paints
  - S13GP:6N/LO-I (S13)
    - Primers: 4044 and 4155
    - Thinners: X-99 and Xylene
  - Aptek 2711
    - MSL paint
- Flex Cable
- M55J composite
- HEPA Filter
- Fiber Optic Cable

Mars 2020 Rover (M2020)

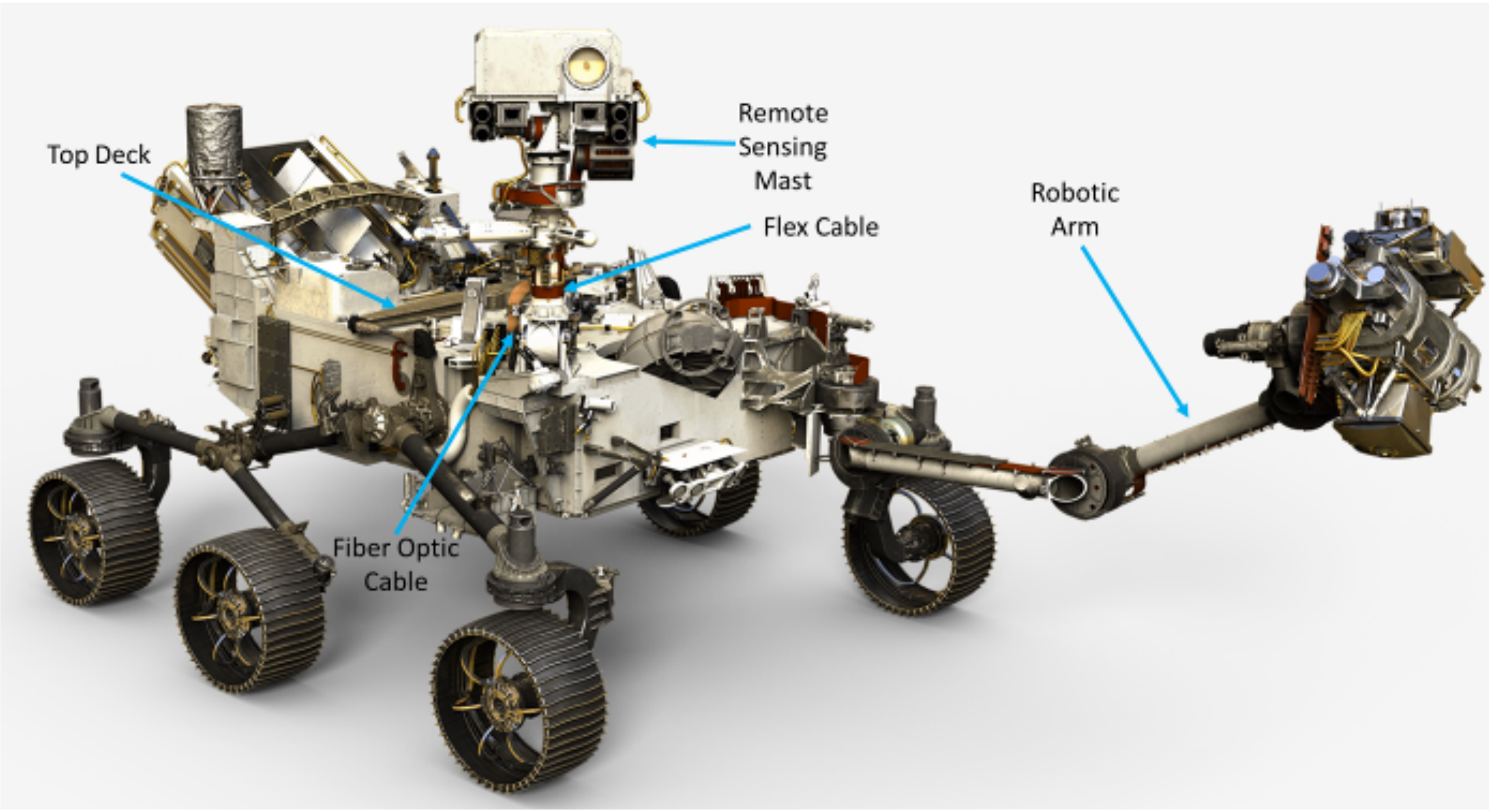
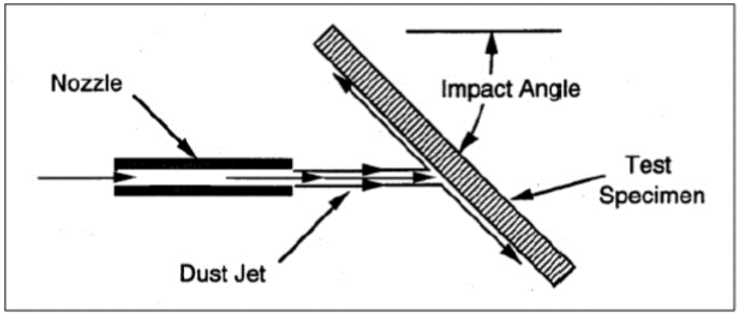


Image courtesy NASA/JPL

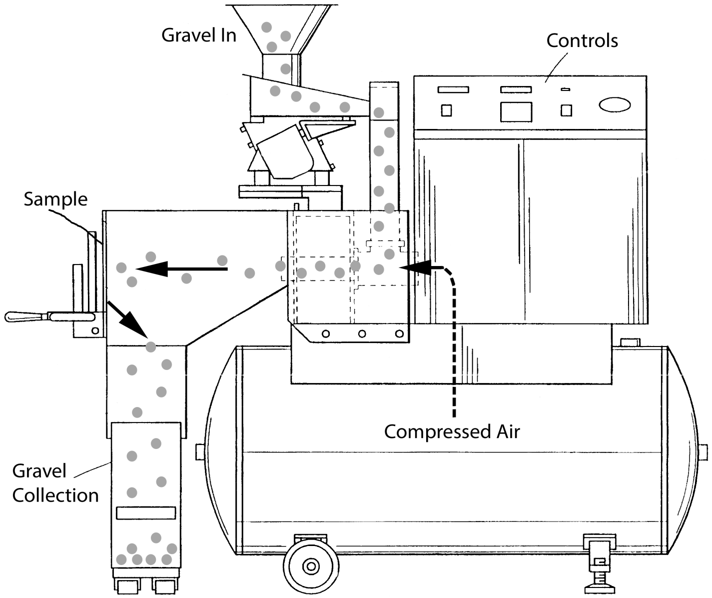
Test Setup

University of Dayton Research Institute (UDRI)

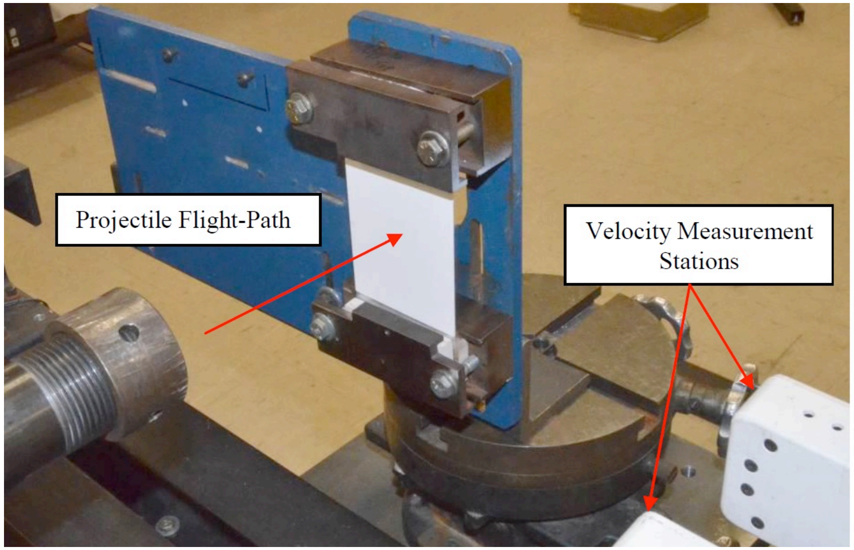
Capabilities



Erosion Rig



Gravelometer



Gas Gun

All instruments used pressurized air to accelerate the particles and lasers to measure particle velocity.

Images courtesy UDRI and
Grossman, D M, S. J. Grossman, G. J. Billington. "Patent US6679095 - Multi-Test Gravelometer." *Google Patents*, Google, Jan. 2004, google.com/patents/US6679095.

University of Dayton Research Institute (UDRI)

Erosion Media

Test Apparatus	Erosion Rig		Gravelometer	Gas Gun
Nomenclature	SAND		GRAVEL	ROCK
Material	Quartz		Basalt	Tonalite
Test Media	Foundry Sand	Golf Sand	Mojave Mars Simulant (MMS) [13]	Cedar City Tonalite
Particle Size	38-44 µm	170-550 µm	1-10 mm	6.4-15.8 mm
Color	brown	brown	red/dark gray	brown
Shape	round	sharp and angular	irregular	machined to a 118° point

Gravel

Rock

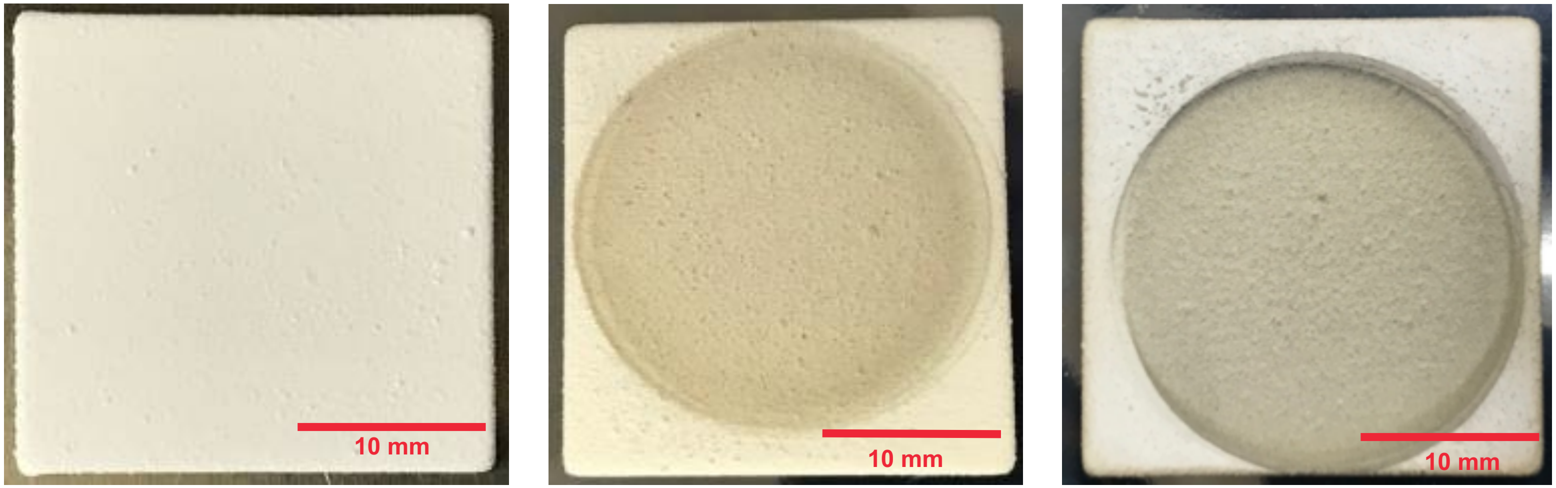
Images courtesy UDRI

Test Matrix

Test Apparatus:		Erosion Rig								Gravelometer	Gas Gun				
Particle Size:		38-44 µm			177-250 µm			240-550 µm		1-10 mm	9.5 mm	12.7 mm	15.8 mm		
Velocity:		250 m/s			160 m/s	80 m/s		85 m/s		25 m/s	20 m/s	22 m/s	22 m/s	25 m/s	
Impact Angle:		30°	60°	90°	30°	30°	90°	30°	90°	90°	90°	90°	90°	30°	90°
MATERIALS	S13 Paint	X	X	X	X	X	X	X	X	X				X	X
	Aptek 2711 Paint				X										
	Xylene Paint				X					X					
	Flex Cable						X	X	X	X					X
	M55J Composite						X	X	X	X					X
	HEPA Filter						X	X	X	X					
	Fiber Optic Cable						X		X		X	X	X		

Results

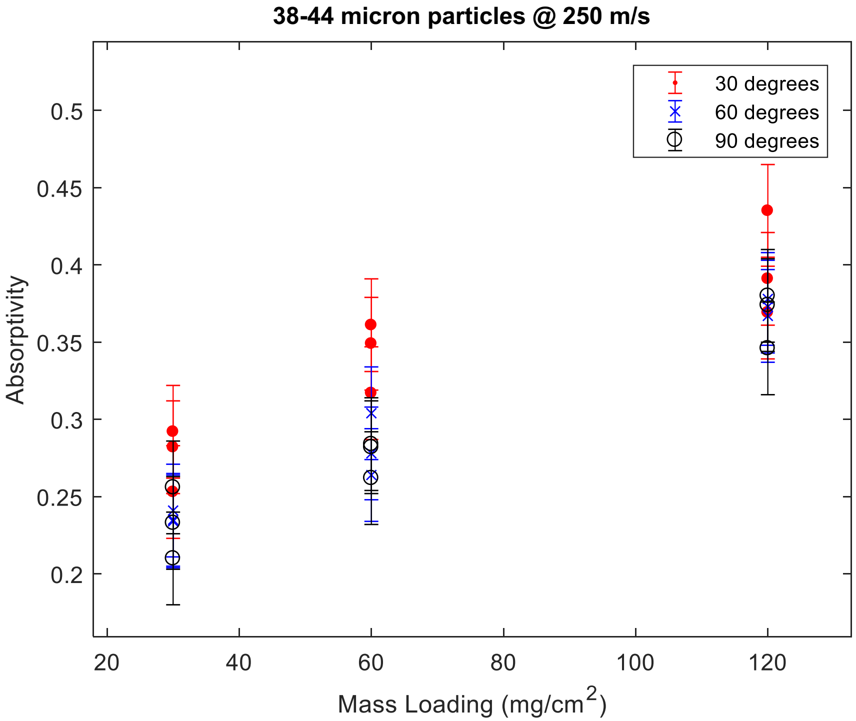
Discoloration of S13 Paint

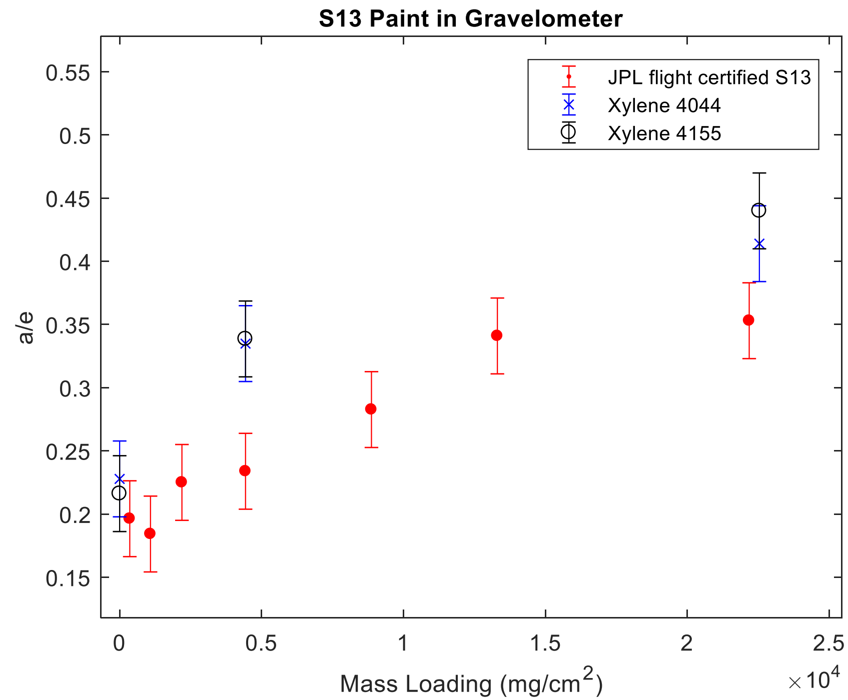


Left: Pristine S13 coupon
Center: S13 coupon exposed to 38-44 micron particles traveling at 225 m/s, 120 mg/cm^2 of total exposure
Right: The same sample after 2000 mg/cm^2 exposure.

Effect: The small particles embed themselves into the soft silicone paint and creating a mass gain and an increase in absorption. Increased absorption effects rover thermal control. The sand used in this erosion test was a white/brown sand; Martian regolith is red so the actual absorption value will differ.

Optical Properties of S13

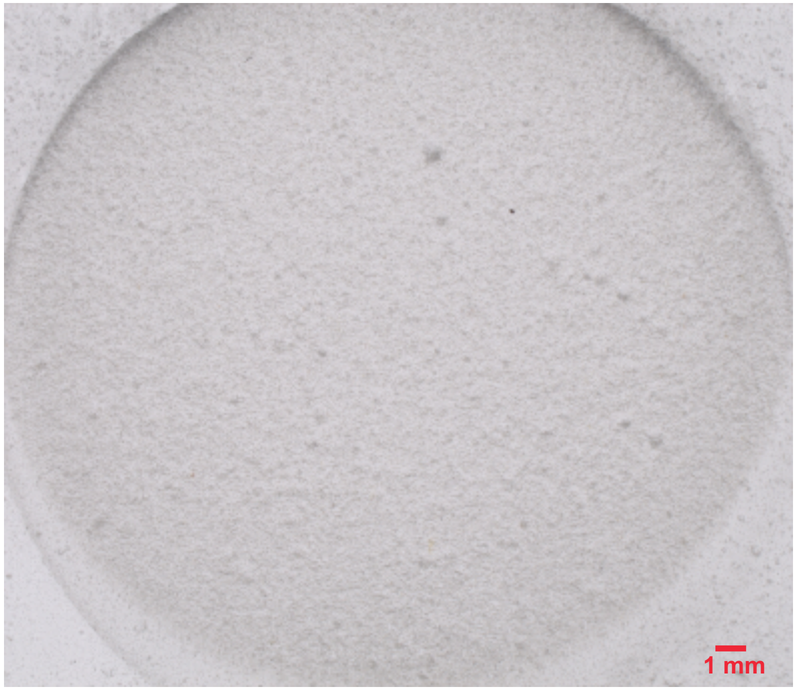


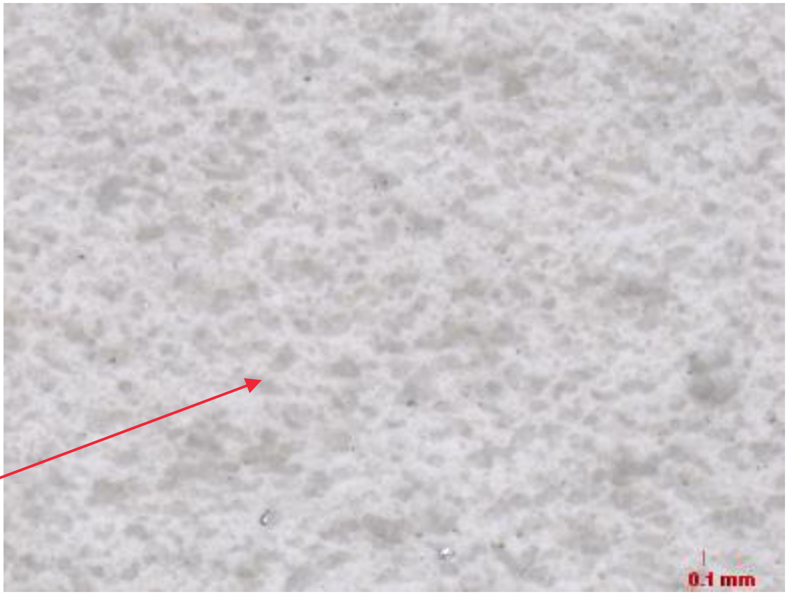


Left: Impact angle had large effect on absorptivity.
Right: The thinners and primers also had an effect on absorptivity.
Emissivity stayed constant.

Sand Embedding in S13 Paint

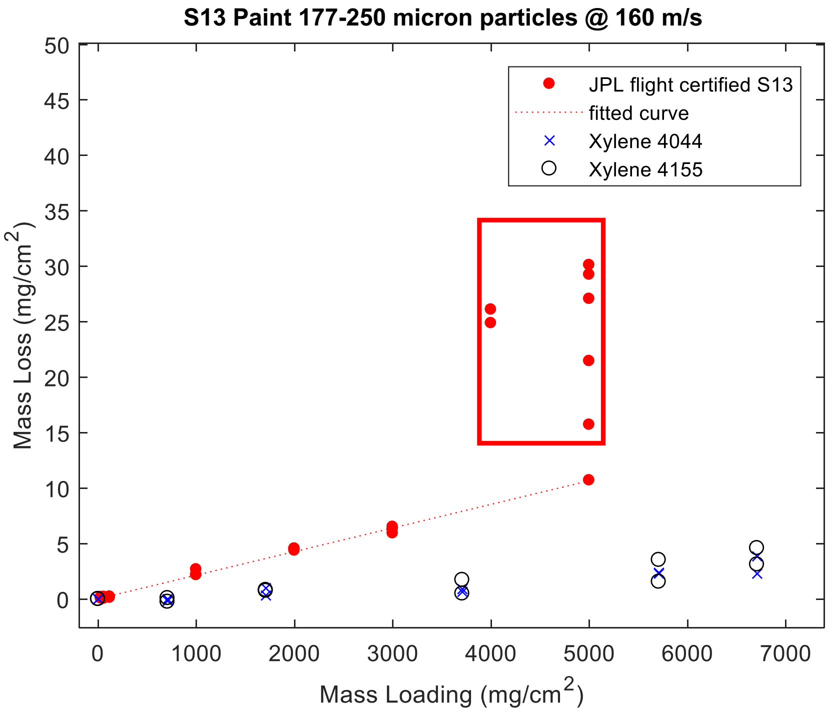
Paint before exposure.

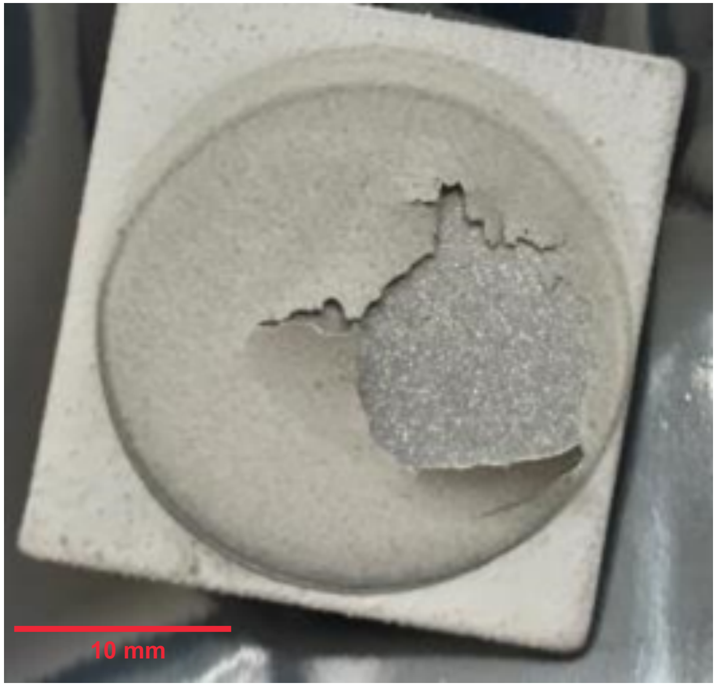




Particles embedded in the paint after exposure to 3000mg at 160m/s 30 degrees 177-250 micron

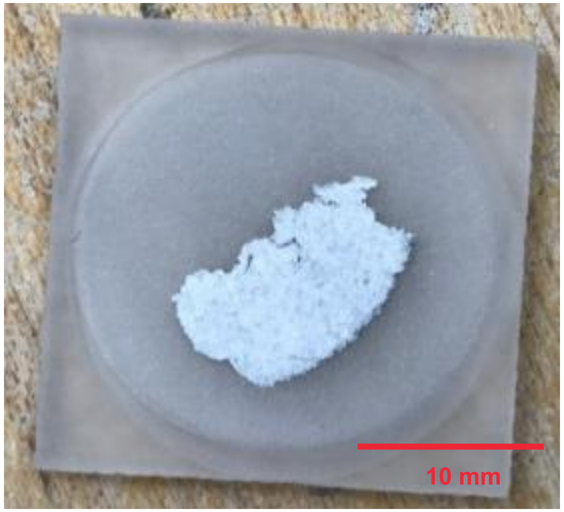
Erosion of S13





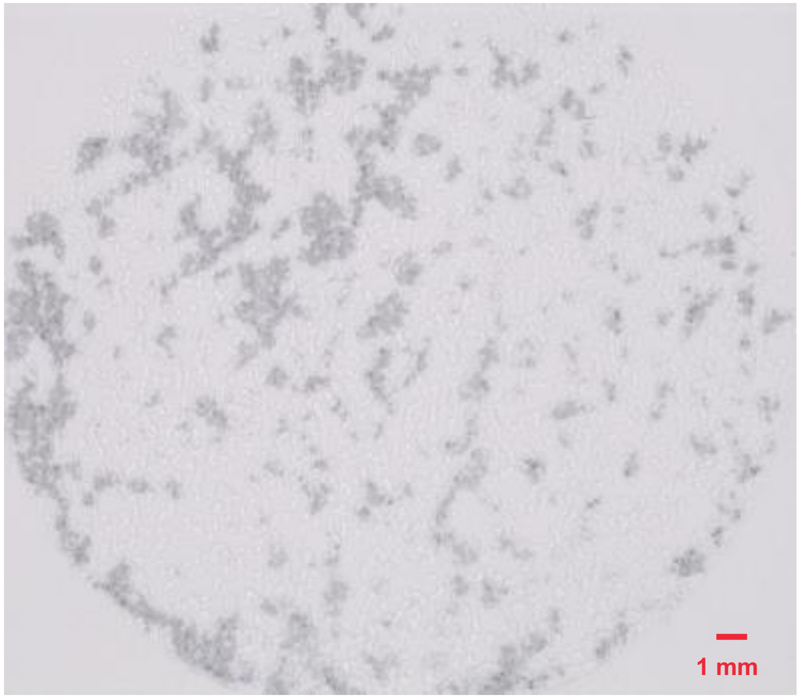
The S13 slowly lost paint until the paint fail catastrophically, detaching from the substrate.
Left: Red box shows which coupons failed.
Right: Image of paint coupon after failure.

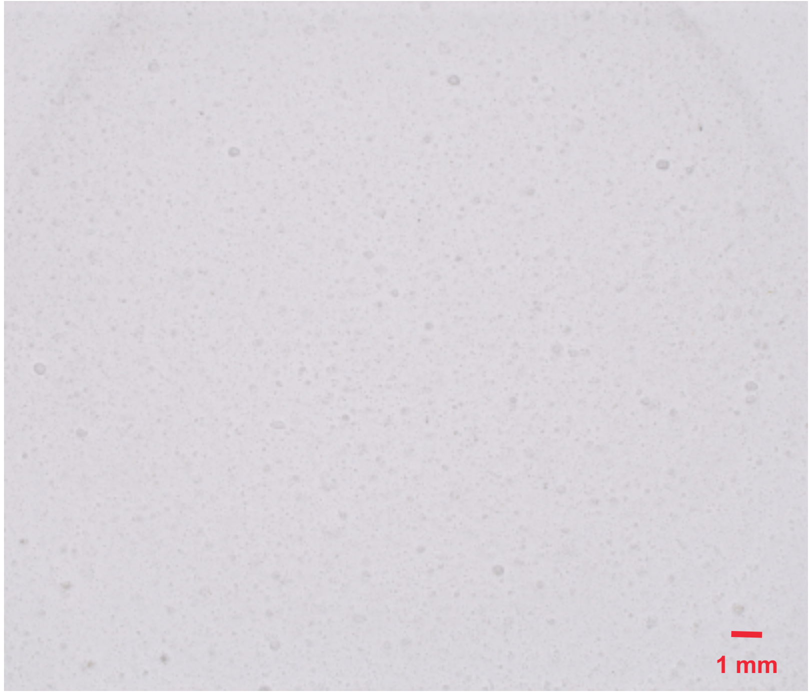
Failure of S13 Paint



S13 paint coupon exposed to 177-250 micron particles at 160 m/s after 5 g/cm^2.
Right: Paint chip found in the sand after testing. The paint chip is about 0.138 in^2, this is 24% of the exposed surface area. This shows the failure mode of the paint is a adhesive failure to the Al substrate.

MSL vs M2020 Paint





Aptek 2711 coupon from Mars Science Laboratory (MSL) (left) and S-13 coupon (right) exposed to the same environment.

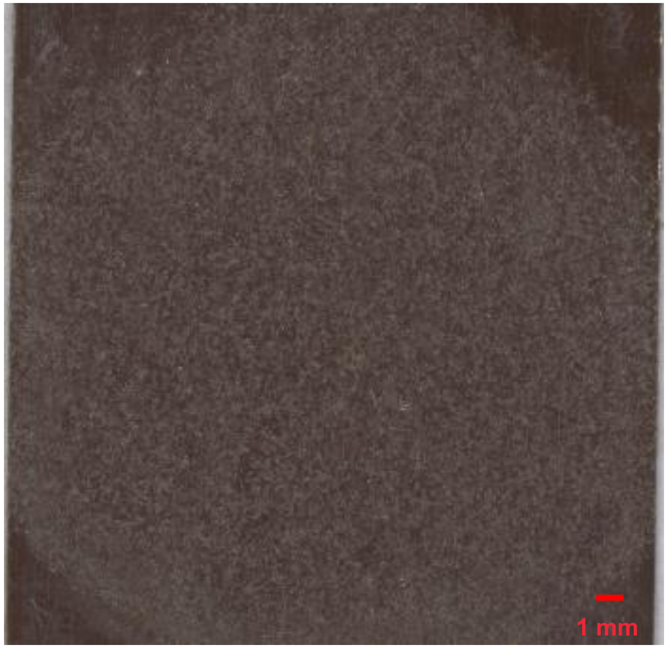
Aptek 2711 is a brittle paint and is prone to chipping.

S13 is a silicone based paint and is soft and prone to peeling but also particle embedding.

Metal trace is not exposed

Flex Cable Erosion

Sand



Gravel and Rock

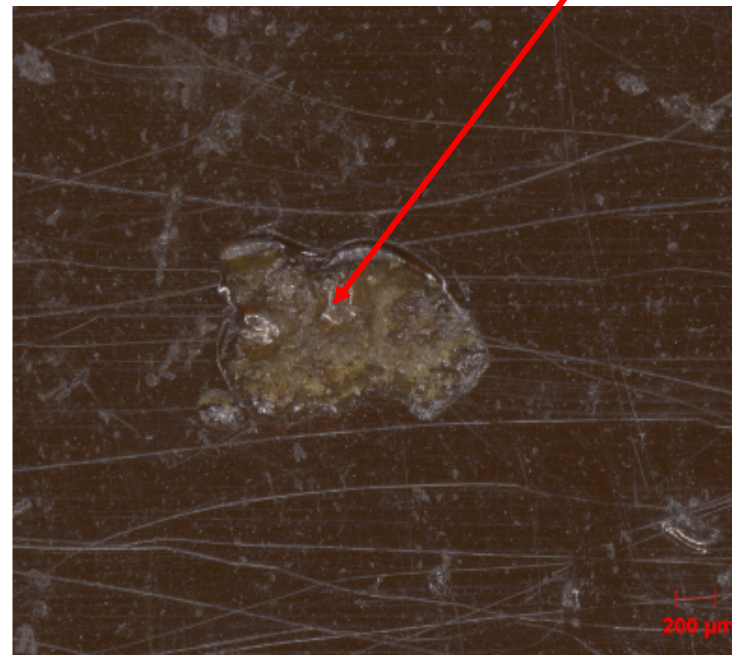
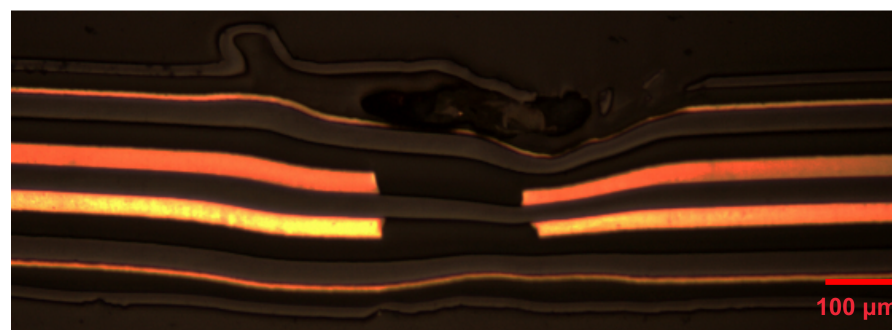
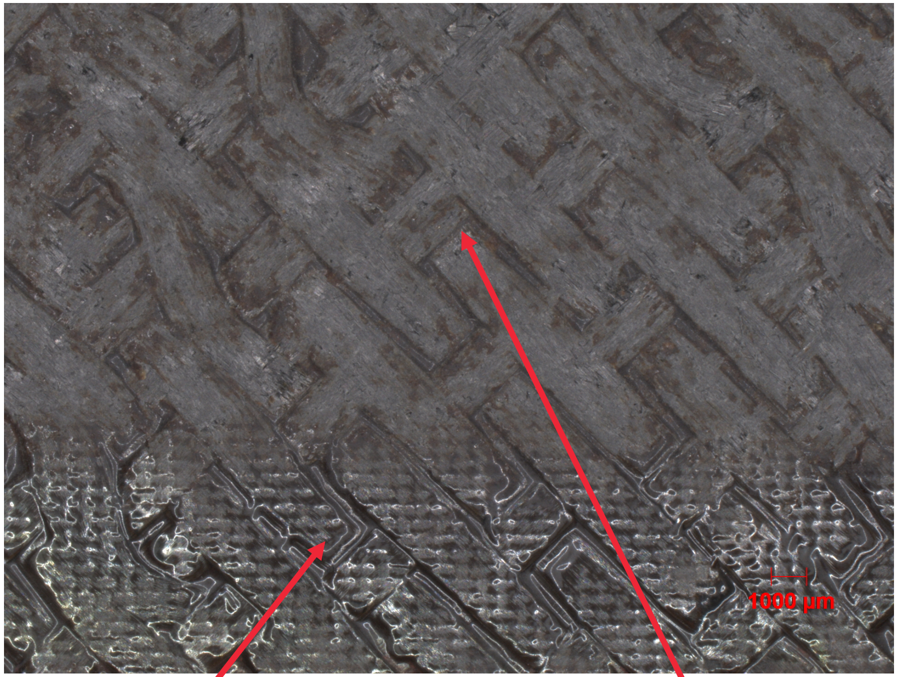


Image and cross-section shows only erosion of the Kapton outer layer.



Worst Case: Cross-section shows no evidence of shorts or opens

M55J Composite Erosion



Not Eroded

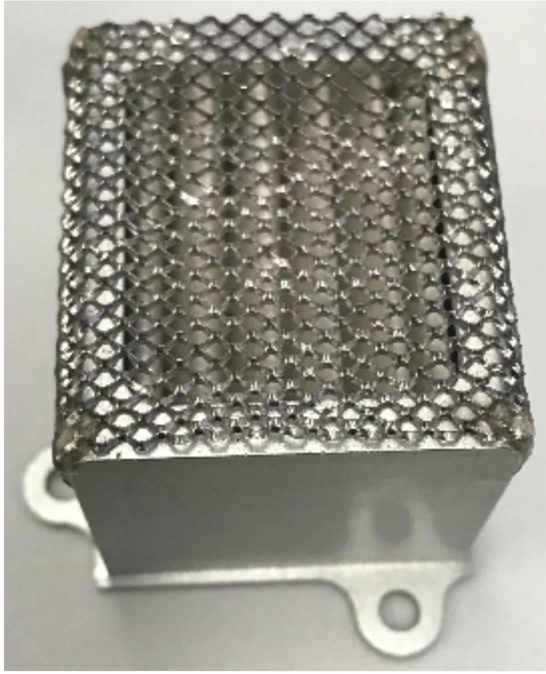
Eroded

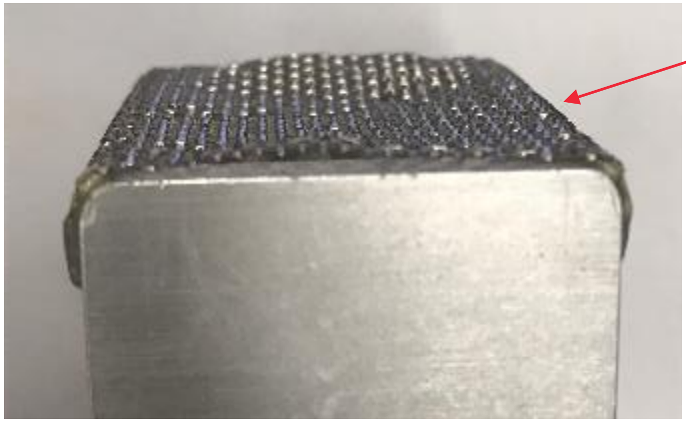
Worst Case: Broken fibers and microscopic through holes.

M55J Composite Gas Gun Particle Impact

Static deformation of about 8 mm after impact from one 15.8 mm particle traveling at 25 m/s

HEPA Filter Erosion



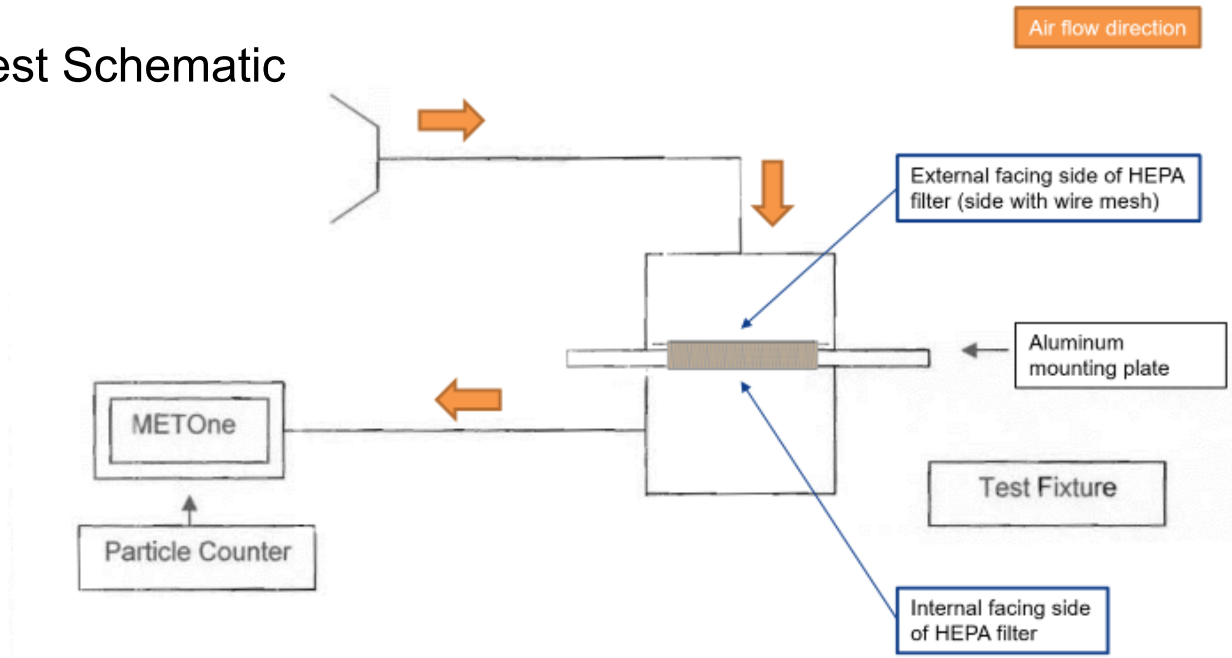


Screen deformed from particles larger than 2 mm.

No evidence of damage from particles < 2 mm.

HEPA Post-Test Particle Count

Test Schematic



Baseline Measurement		
Time	Count	
min	0.3 micron	0.5 micron
1	116101	16139
2	116820	16830
3	123836	17903
4	121680	17596
5	113146	16456
6	122199	17719
Average	118963.6667	17107.16667
Baseline	0.3 micron	0.03% of Average
	118963.6667	35.7

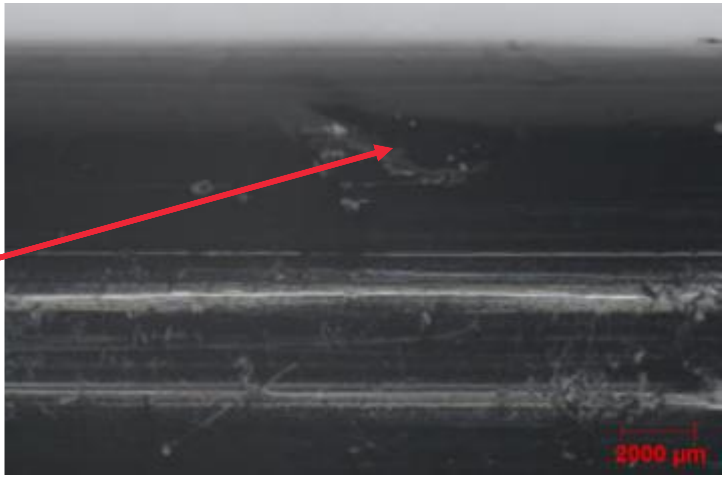
RSM Chassis HEPA Filter Post- Test Measurement		
Time	Count	
min	0.3 micron	0.5 micron
1	23	4
2	14	3
3	13	0
4	16	0
5	19	0
Average	17	1.4
Result	Pass	
Highest Value	23	

Images courtesy Lemil Cordero

Fiber Optic Cable (FOC)

Deformed <1.15”

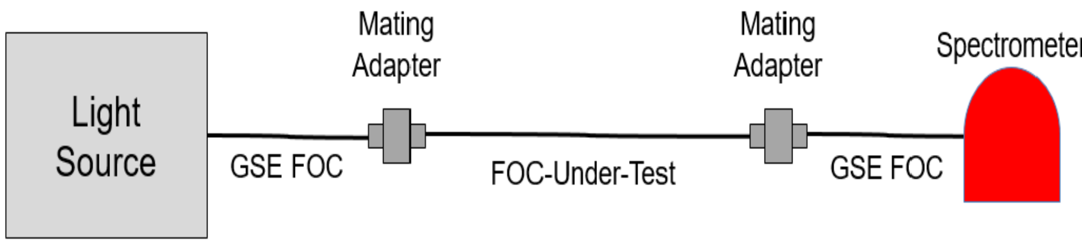
Deformed ~2”

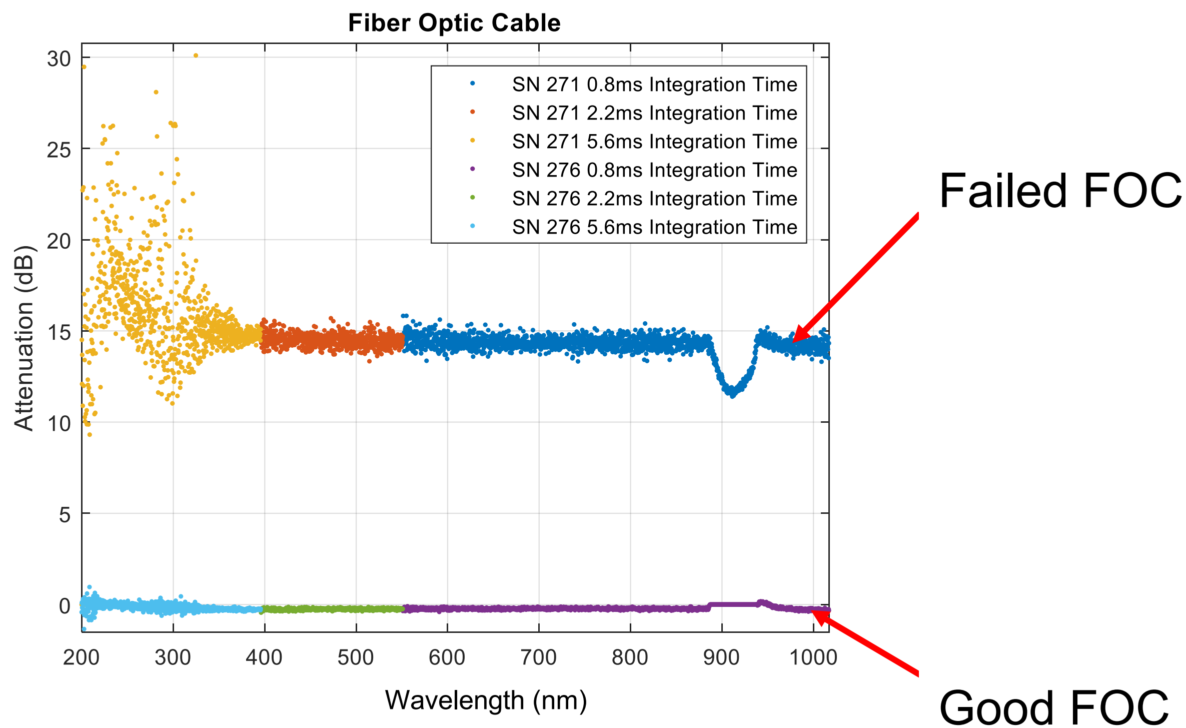


Indentation in the FOC jacket

FOC Attenuation Measurements

Test Schematic





Images courtesy Jeffrey Carlson

Conclusion

- All material tested will survive the predicted high-velocity particle environment that the M2020 rover is expected to be exposed to when it lands on Mars
- An increase in the α/ε ratio due to particle embedment for the S13 paint was observed; this change in optical properties needs to be accounted for in a system level thermal analysis.
  - Once particles are embedded in the paint, there is a low likelihood of the particles migrating off of the painted surface, which means that the increased α/ε ratio will likely remain
- The paints with 4155-xylene and 4044-xylene where able to withstand higher velocities and mass loading then the current M2020 paint.
- This testing will help plan future missions to Mars and other aerospace locations.

Thank you to…

- Caltech, JPL, and NASA
- Mars 2020 Program Office
- University of Dayton Research Institute
  – Cheryl Castro
  – Kevin Poormon
  – Matt Rothgeb

Biography

Emma Bradford *received a B.S. in Applied Physics with a minor in Chemistry from Xavier University in 2014. She has been at JPL for 4 years and works in the Materials Laboratory. There she tests materials in simulated space environments. Missions Emma has worked on include InSight, Mars 2020, MAIA, DSOC, and Psyche.*

Jason Rabinovitch *is a Mechanical Engineer at the Jet Propulsion Laboratory (JPL), California Institute of Technology, where he works in the Entry, Descent, and Landing & Formulation Group. Prior to JPL, Dr. Rabinovitch received a B.Sc. in Mechanical Engineering from Yale University in 2008, a M.Sc. in Aerospace Engineering from the California Institute of Technology in 2009, a M.Sc. in Fluid Mechanics from École Polytechnique (Paris) in 2010, and a Ph.D. in Aeronautics from Caltech in 2014. Dr Rabinovitch is a member of the AIAA Thermophysics Technical Committee, and his research interests span a wide range of topics related to experimental and computational fluid mechanics applied to EDL, vehicle design, propulsion, ablation, and geophysical applications.*

Dr. Mohamed Abid *received PhD in AME from University of Southern California. He is the Deputy Chief Mechanical Engineer for M2020. He was the Manager for the Mechatronics group at JPL, and the Mission Chief Engineer of Soil Moisture Active Passive (SMAP) mission. He is the author of the textbook: "Spacecraft Sensors" a John Wiley & Sons publication*.

Jet Propulsion Laboratory
California Institute of Technology

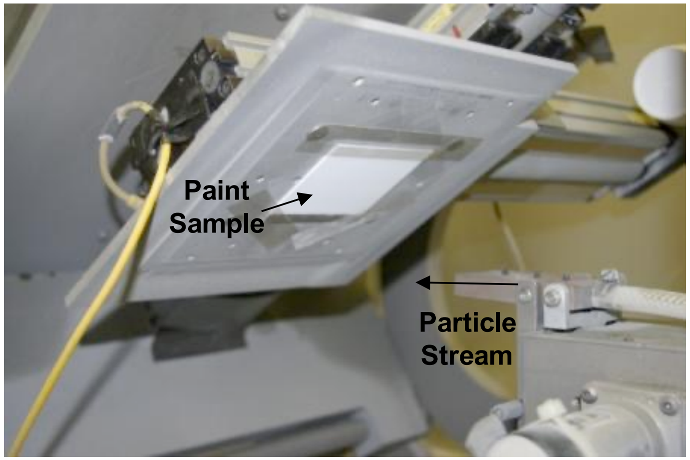
jpl.nasa.gov

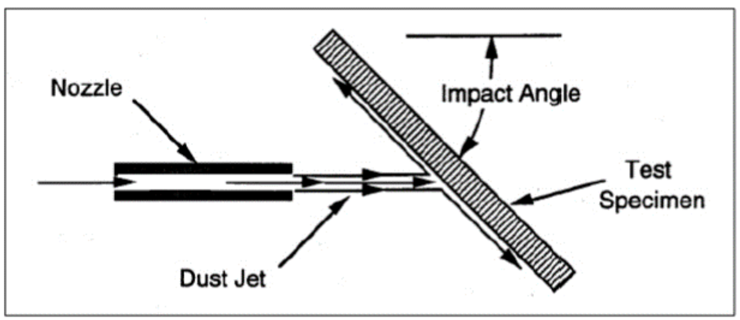
Backup Slides

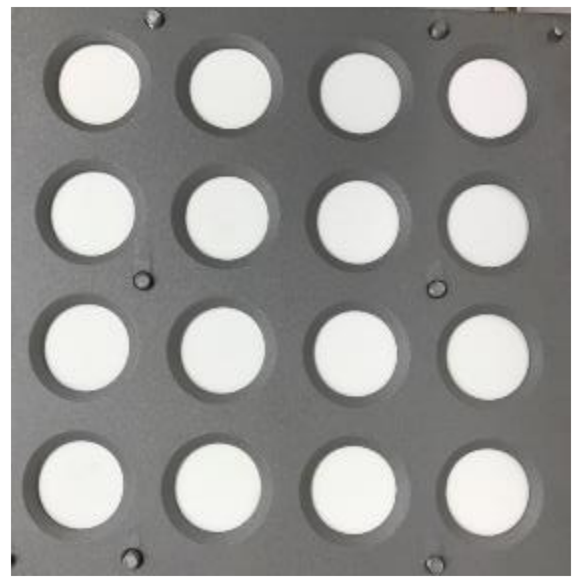
Plume/ Surface Interactions

Image courtesy: Vizcaino, Jeffrey, and Manish Mehta. "Quantification of Plume-Soil Interaction and Excavation Due to the Mars Science Laboratory Sky Crane Descent Phase." *8th Symposium on Space Resource Utilization*, Feb. 2015, doi:10.2514/6.2015-1649.

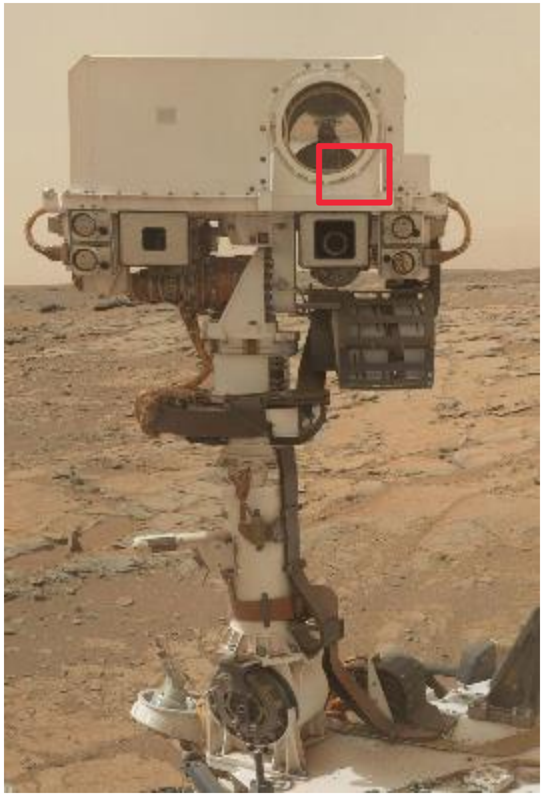
Sample configuration for paint, flex cable, and M55J composite



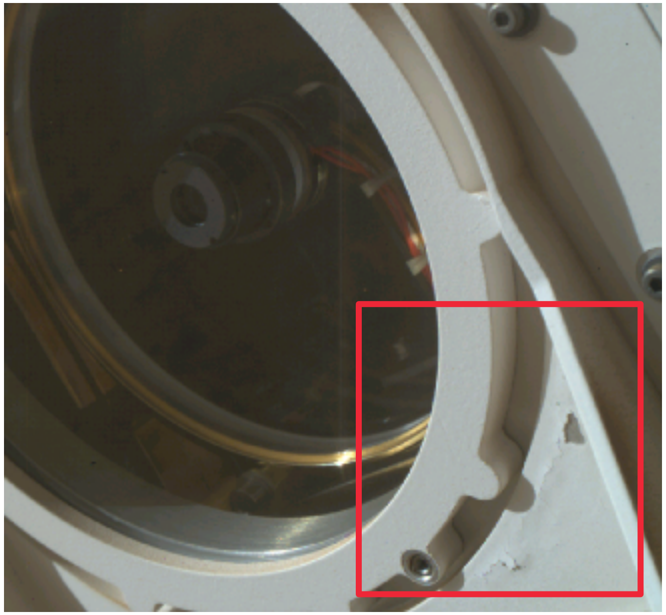




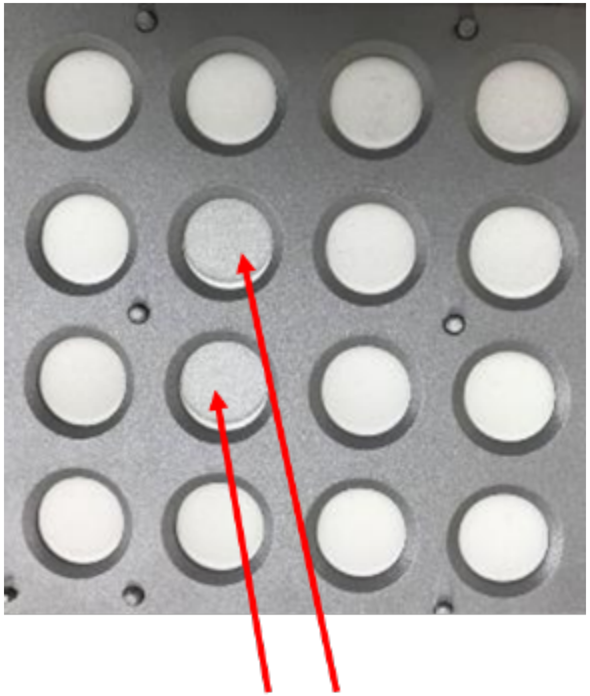
Failure of Aptek 2711 (MSL Paint)



Sol 177



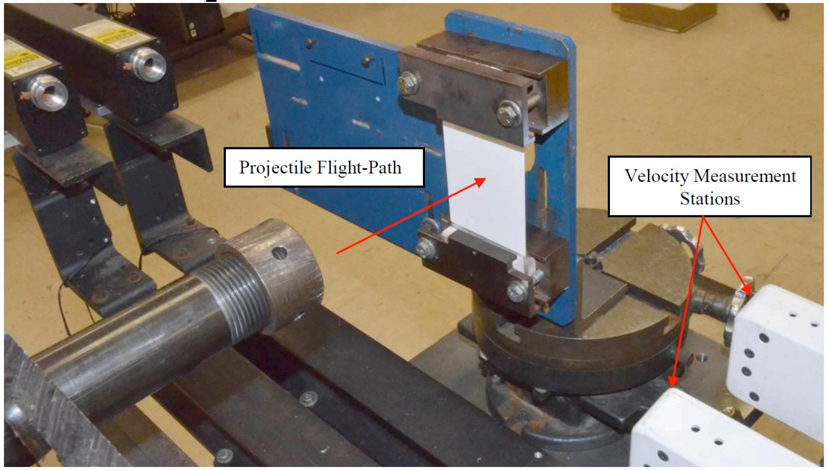
Sol 601

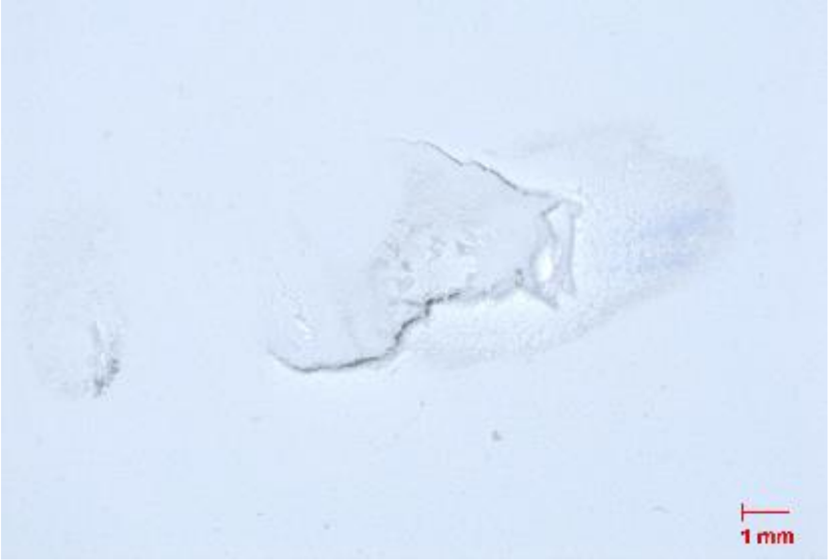


MSL Paint shows
bare Al

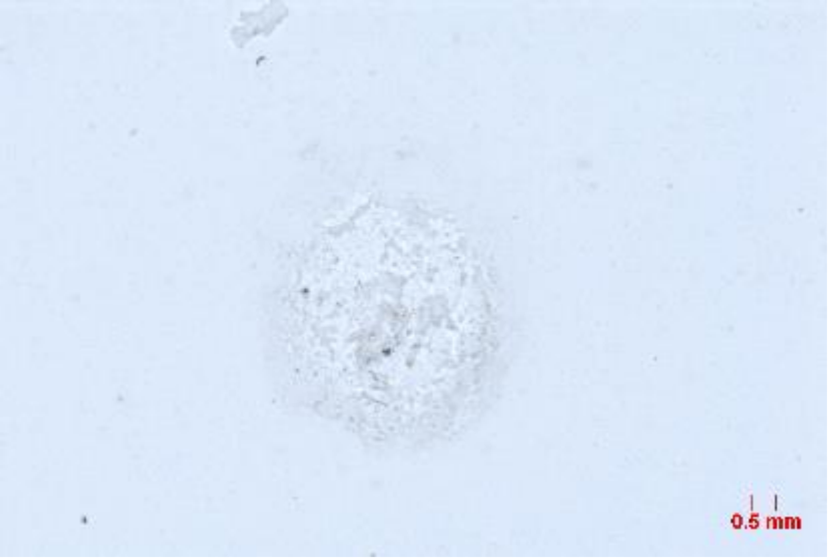
Images courtesy NASA/JPL

Gas Gun Setup and Particle Impact



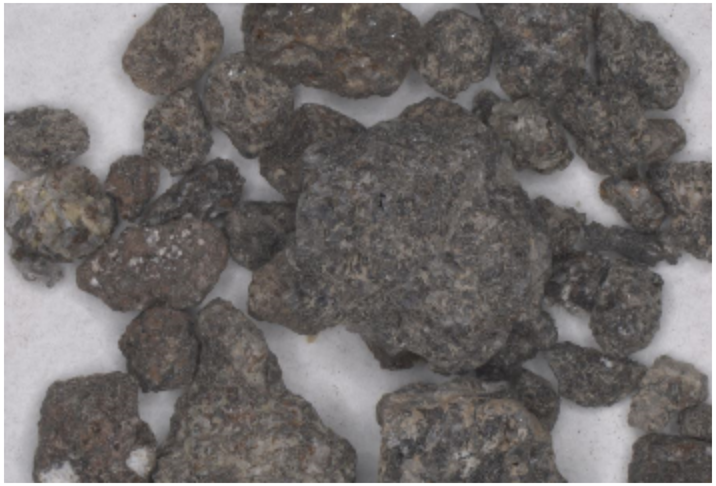


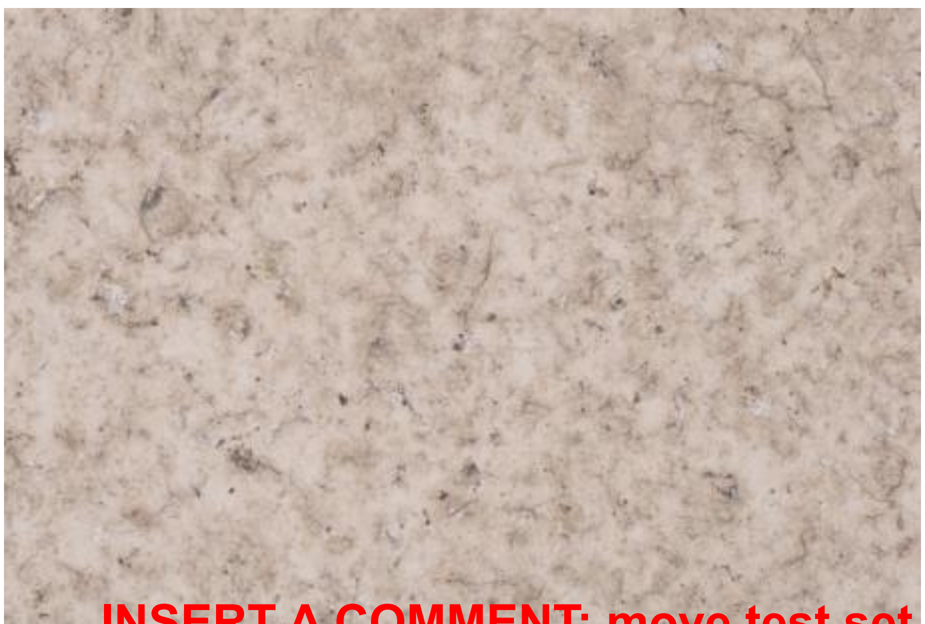
15.8 mm particle impact at 30°

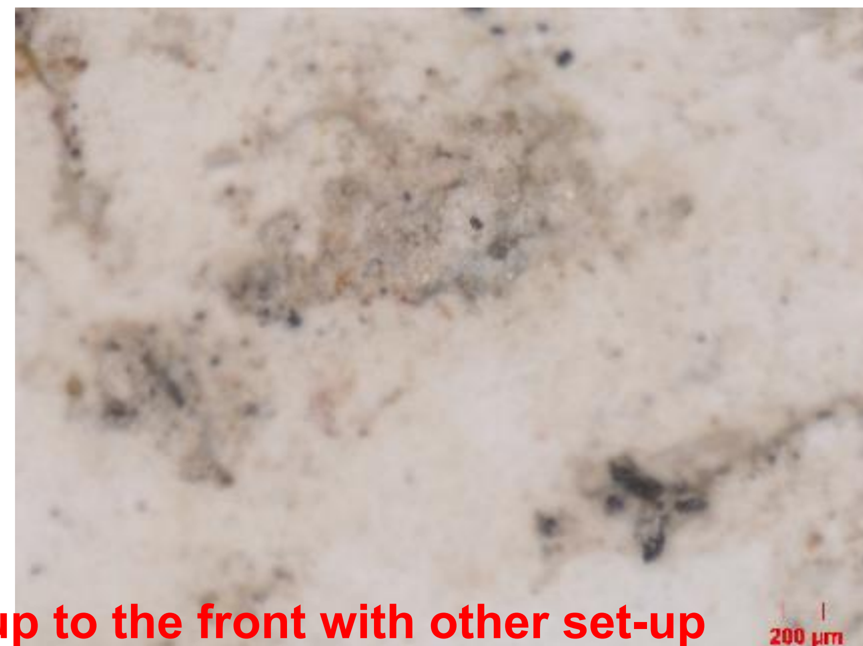


15.8 mm particle impact at 90°

Gravelometer Erosion of S13



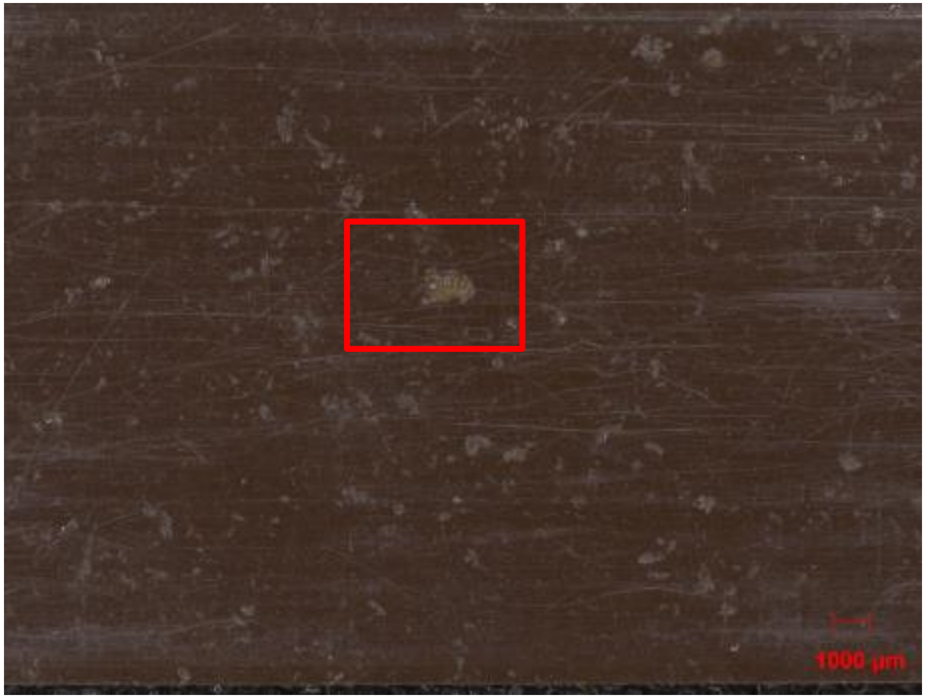


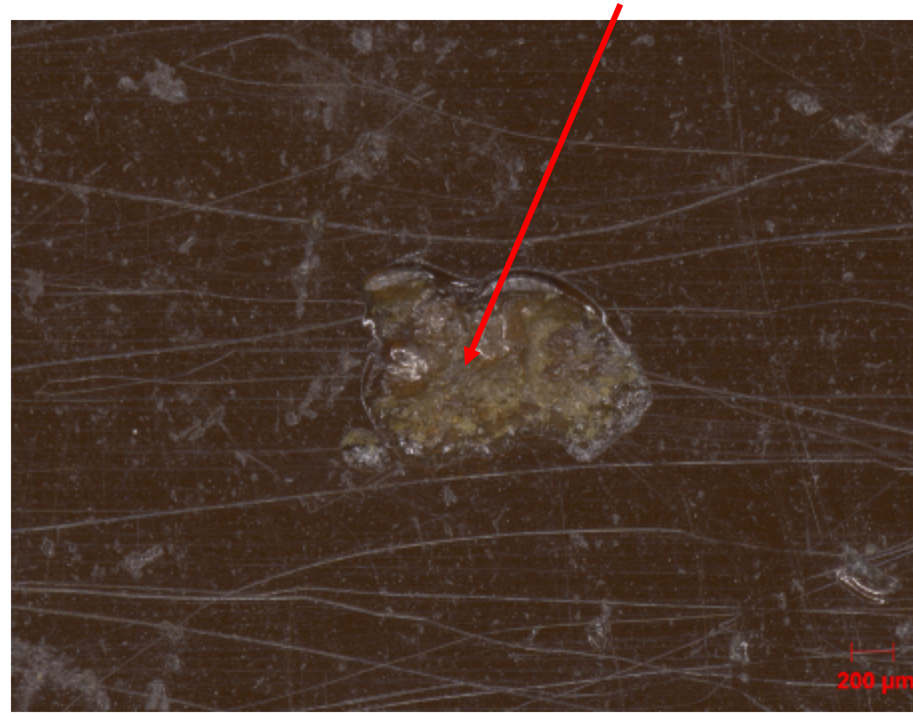


INSERT A COMMENT; move test set up to the front with other set-up

Flex Cable Gravelometer Erosion

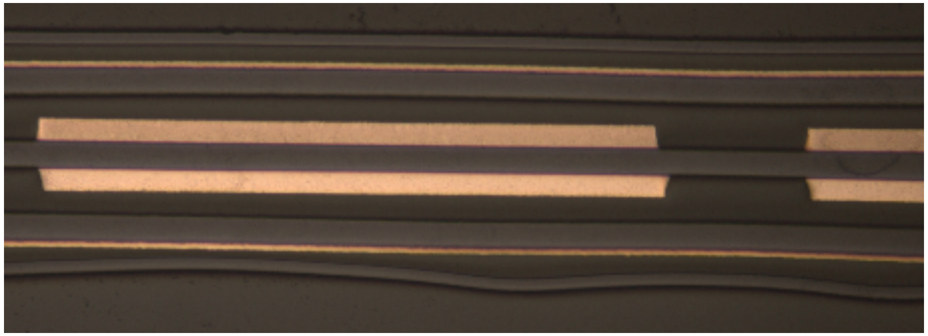
Metal trace is not exposed

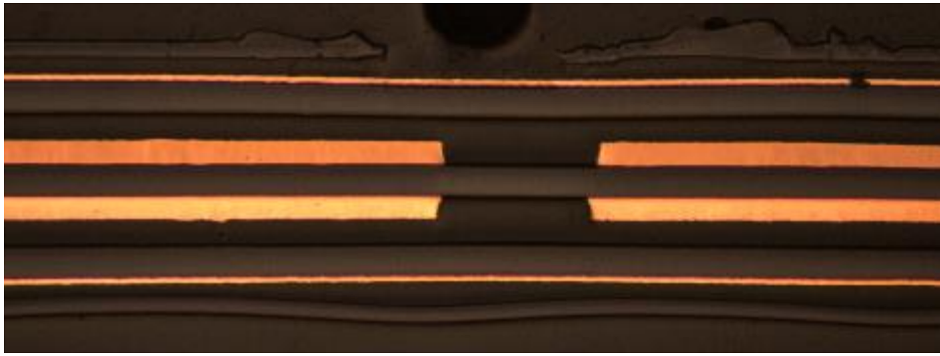
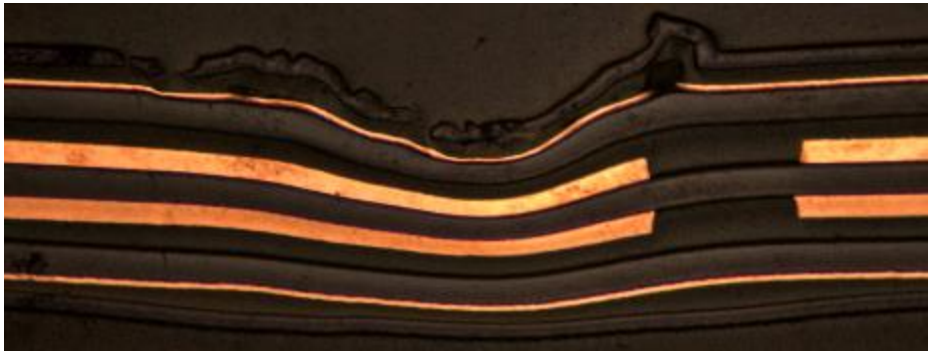
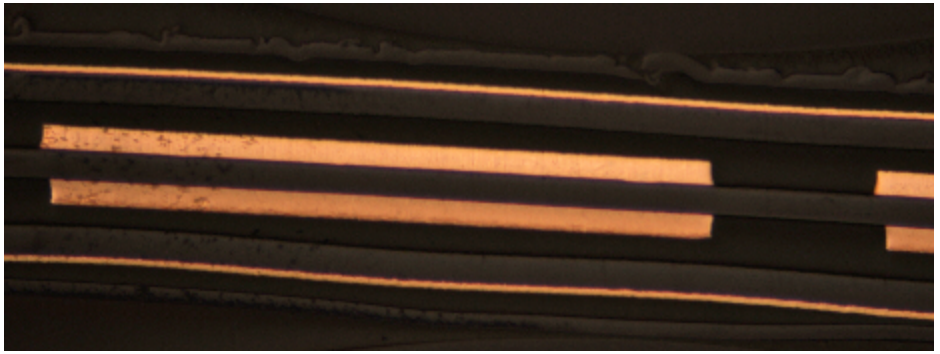




Cross-section shows no evidence of shorts or opens

Flex Cable Cross-Sections

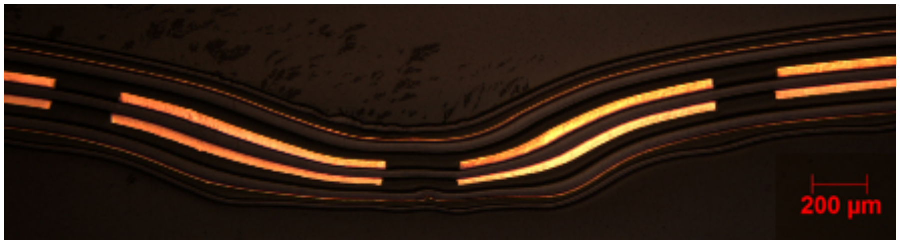


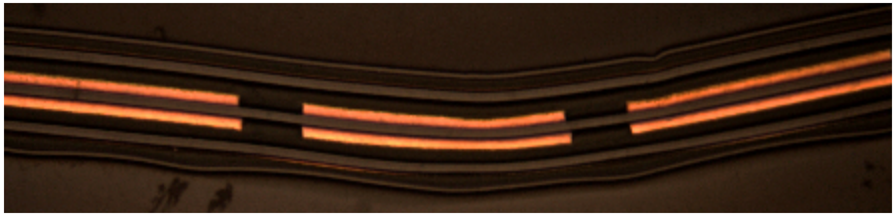
INSERT A COMMENT; SHOW STORY

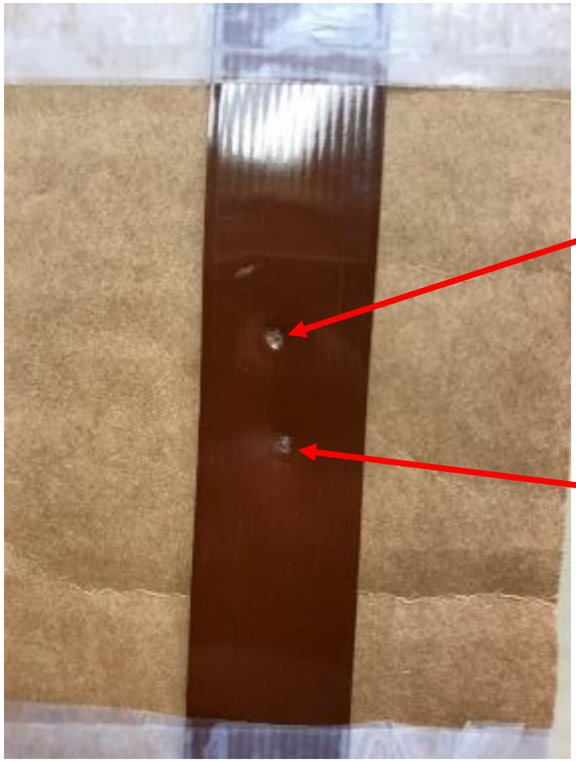
Flex Cable Gas Gun Particle Impact

Flex attached to Al



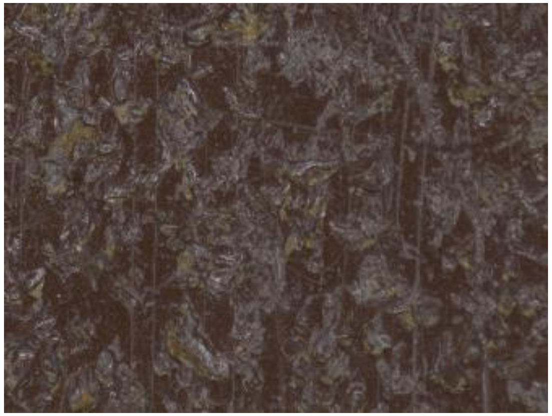
Flex attached to Cardboard



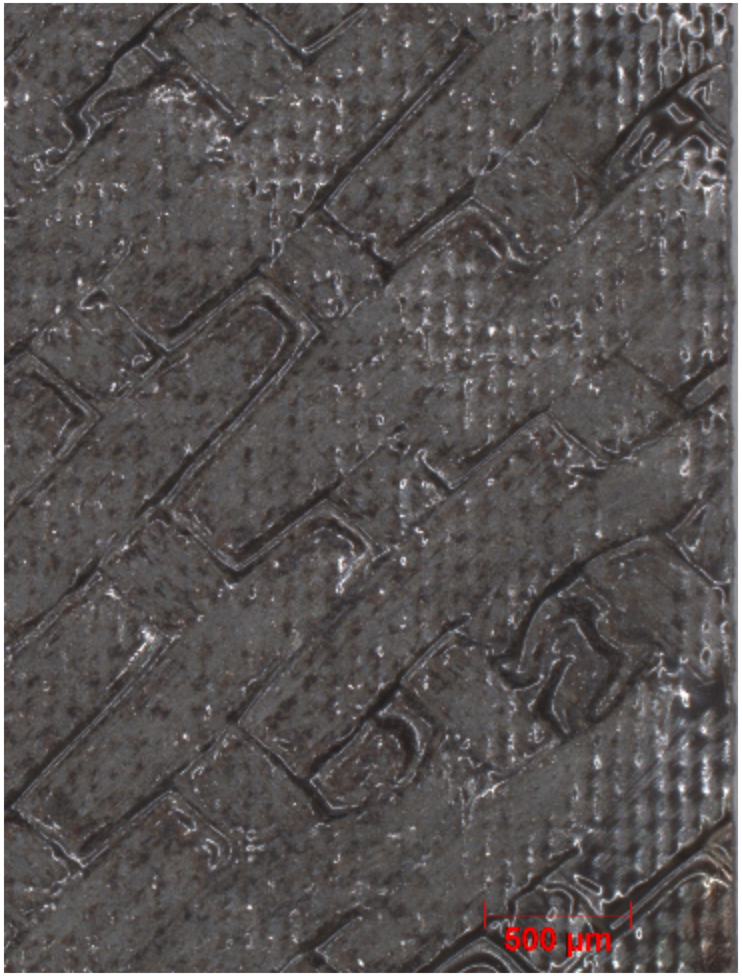


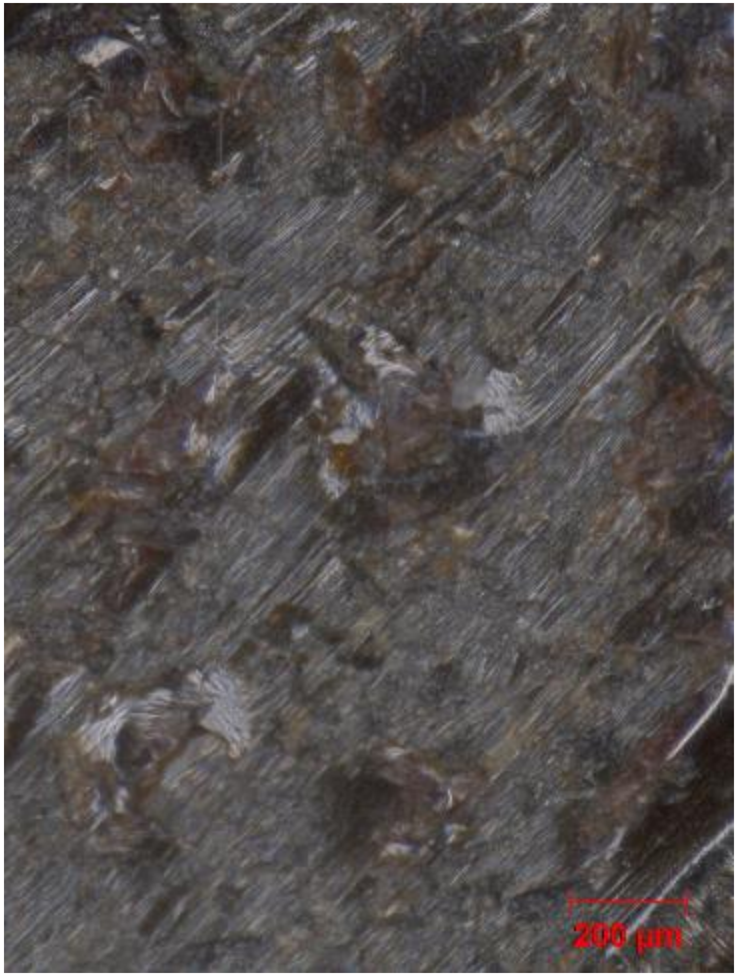
Impact with Al behind Flex Cable

Impact with cardboard behind the Flex Cable



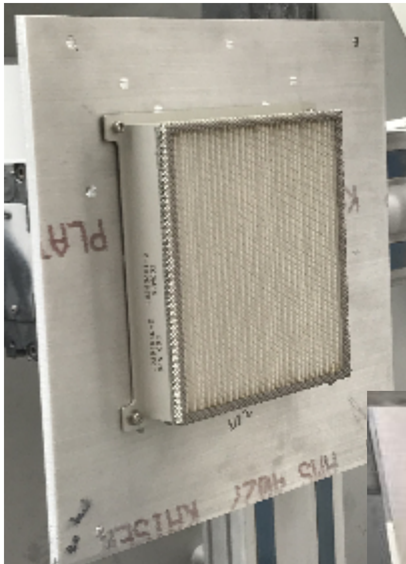
M55J Composite Sand Erosion

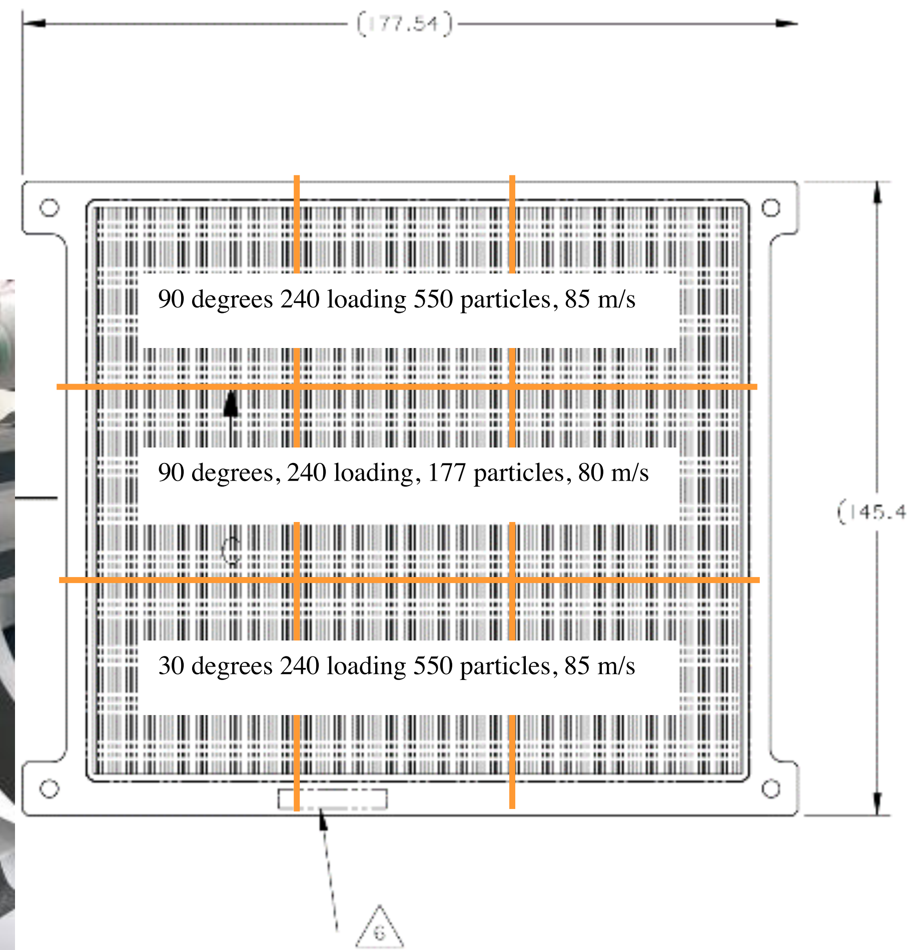




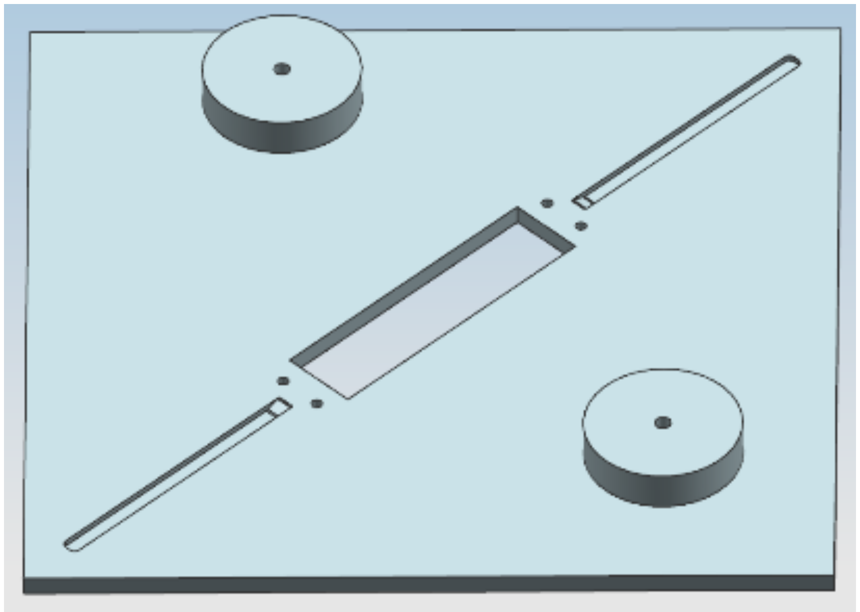
INSERT A COMMENT

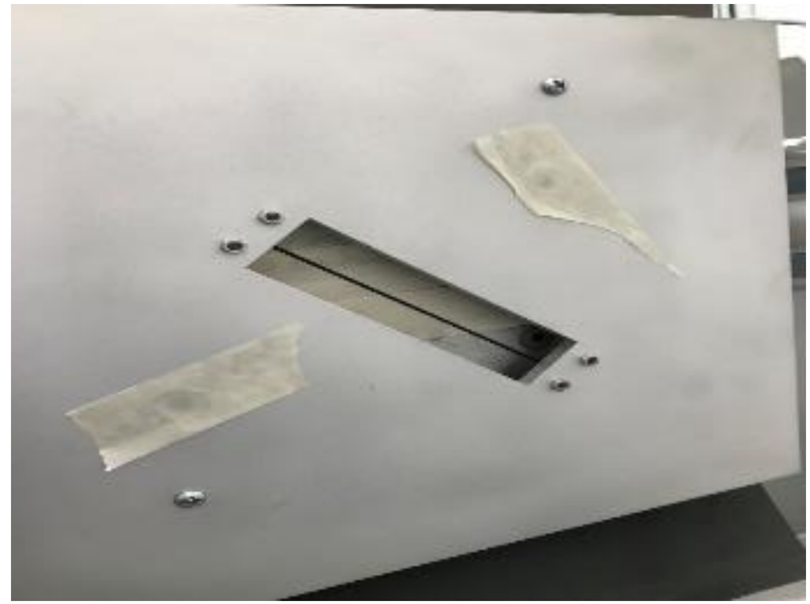
HEPA Filter Setup in the Erosion Rig



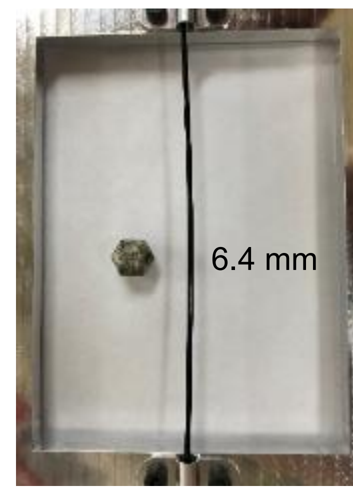


Fiber Optic Cable Setup in the Erosion Rig



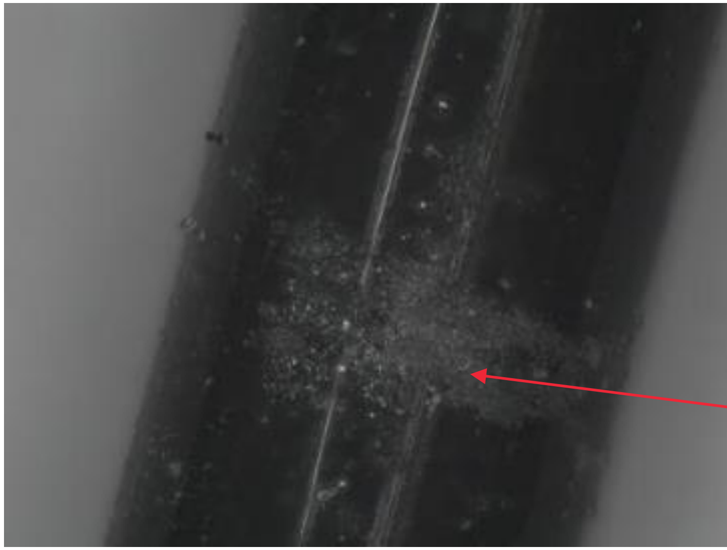


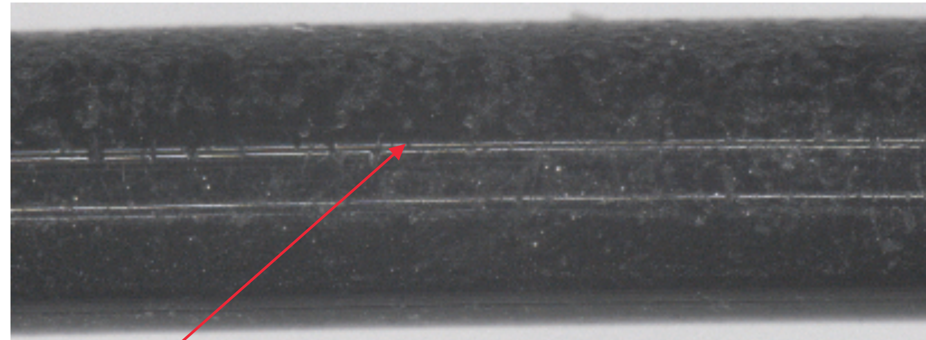
Fiber Optic Cable Gas Gun Setup



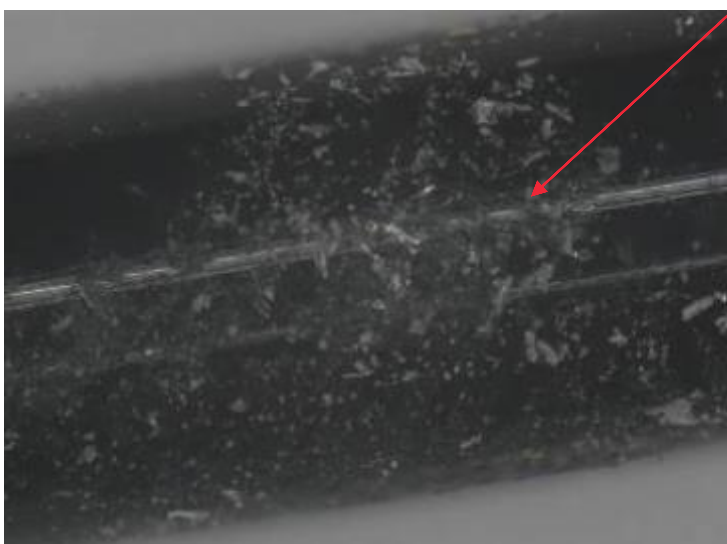
- Fiber Optic Cable deformed about 2” after impact from a 15.8 mm particle traveling at 20 m/s
- Maximum deformation according to manufacture is 2”
- Preliminary attenuation measurement show light dimmer than pre-test
- Post-Test attenuation measurement all pass but one

Fiber Optic Cable





Particles imbedded in the FOC jacket and scratches



Indentation in the FOC jacket